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TITLE

EVALUATION OF BIDIRECTIONALLY CONDUCTING THYRATRONS

FOR PULSED EXCIMER LASERS

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EVALUATION OF BIDIRECTIONALLY CONDUCTING THYRATRONS FOR PULSED EXCIMER LASERS

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Abstract

In the last few years many new applications have been found for excimer lasers in industry and defense programs. Many of these programs have very stringent requirements of lifetime, reliability, and power that are not available commercially. Power conditioning systems capable of driving excimers with reliable lifetimes of 5 billion pulses have been built with off-the-shelf components. In this paper we will discuss the requirements and life test performance of three types of thyratrons designed specifically for driving excimer lasers and also the life of associated components.

Introduction

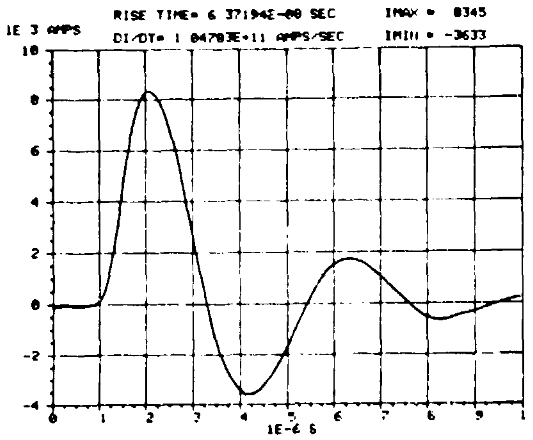
The low steady state impedance of an excimer gas load makes matching the energy storage element difficult or prohibitively complicated for high reliability. Impedance matching can be accomplished with the use of low Z water or dielectric lines [1] and double pulse techniques [2]. However, these methods have not been shown to be scalable to high average power and rep rate and still maintain a high degree of reliability. Impedance matching in the common commercial type circuits such as the pulse charge line or LC inversion circuit can be achieved but at the sacrifice of efficiency. For example, using helium as a buffer gas will maintain a higher breakdown impedance thus a higher electrical efficiency but the kinetic efficiency will suffer. To achieve a higher kinetic efficiency argon or neon is used, but the discharge impedance will be lower and matching will be difficult. Having a load of a lower impedance than the driving circuit reflects very demanding electrical requirements on the switch. Both of these circuits perform equally well in driving lasers and in subjecting the switch to a high value of voltage reversal. When a negative voltage of 600 to 800 V is impressed on the anode, the hydrogen ions present after conduction can reach a destructive potential and cause damage to the tube electrodes. Negative anode voltage can also cause reverse arcing from the cathode that can evaporate or oblate the emissive coating onto adjoining electrodes and cause severe damage to the cathode surface. The hollow or box [3] anode thyratron is unaffected by the destructive forces associated with reverse voltage and current. This type of thyratron can conduct in the reverse direction at high average powers with no reduction in life. The fundamental principles of design and operation of the hollow anode thyratron are beyond the scope of this paper and will not be addressed. Rather we will concentrate on the application of these devices in pulsed laser circuits.

Evaluation in Test and Laser Circuits

Three different sizes of hollow anode thyratrons were chosen to be evaluated for their switching, life, and power-handling performance. These were the EEV CX-1573C, CX-1574, CX-1574C, and the CX-1625. Electrical parameters of the discharge circuit were designed to simulate the switching demands of a directly driven laser or one with a magnetic pulse sharpening stage between the switch and the laser cavity. Test circuits were designed to duplicate or exceed the values of current and voltage the thyratrons would encounter in the laser in which they would be used. The waveforms in Fig. 1 show the current waveforms for the CX-1574C and Fig. 2 for the CX-1625. Performance of the thyratrons was determined in the simulation circuit in order that long (greater than 1000 h) uninterrupted test could be made which are not possible with an excimer laser.

The first tube investigated was the CX-1574 tetrode [4]. Three of these tubes were tested, two to end of life. A chart of the tube discharge parameters for both the test circuit and the laser circuits are seen in Table 1. Two important factors were found that improved the performance and life of the CX-1574s. First, for short pulses with high di/dt operation, triggering both grids [4] made a marked improvement in switching time and jitter. Peak-to-peak jitter for these tubes was a maximum of ±1 nS when new and ±2.5 nS at end of life. The second point involves life extension. It is well known that the cathode emission is mainly from the upper portion of the cathode structure when the thyratron is used in a short pulse circuit. This too was true of the first CX-1574 tested to life. Measurements of cathode emission made over the life of the tube indicated that failure was due to loss of emission. An autopsy confirmed the measurements. To increase the emission and use more of the cathode surface the heater voltage was increased from the nominal 6.3 to 6.8 VAC. The second tube run with the increased heater power had a factor of 6 increase in life. The autopsy of the second tube revealed that the tube had failed due to cathode depletion. Unlike the first tube, the cathode of the second CX-1574 had been uniformly depleted over the entire surface. The second CX-1574 life test was stopped at 1.25×10^{9} shots when the jitter of the thyratron exceeded the 5-nS peak-to-peak constraint set on the test.

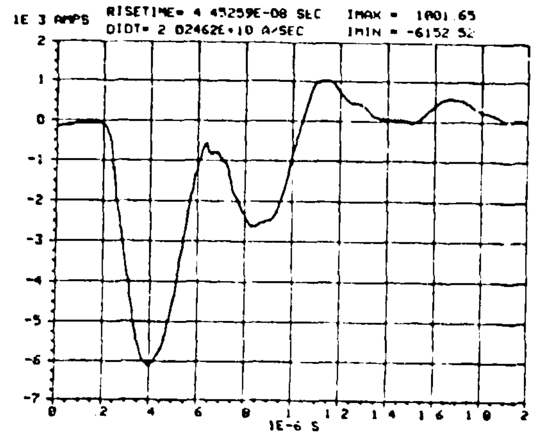
Next to be tested was the pentode version of the CX-1574, the CX-1574C. As done with the three previous CX-1574s, the C version was thoroughly tested with respect to triggering, switching, jitter, etc. A major difference was found in the comparison of the



CX-1574C TEST CIRCUIT CURRENT WAVEFORM

2kA/div Vert 100nS/div Horz

Figure 1a.



CX-1574C LASER CIRCUIT CURRENT WAVEFORM

1kA/div Vert 200nS/div Horz

Figure 1b.

TABLE 1

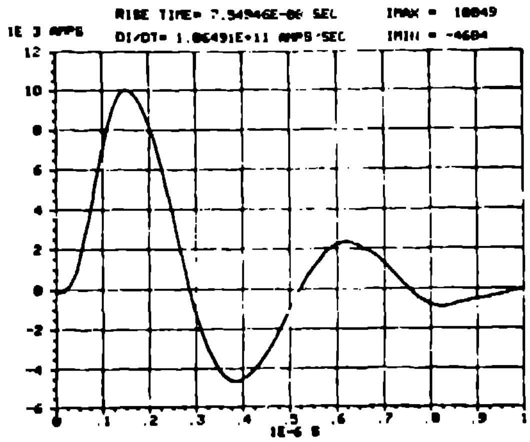
DATA OF HOLLOW ANODE THYRATRONS

HOLLOW ANODE TEST CIRCUITS

DEVICE	e_{py}	i_b	i_r	IRMS	PRR	di/dt	LIFE	FAILURE MODE
	(kV)	(kA)	(kA)	(A)	(pps)	(A/sec)	(SHOTS)	
CX-1573C	35	11	5	90	250	2×10^{11}	2.8×10^{6}	GRID WARPING DUE TO OVERHEATING
CX-1574 #1	25	8.5	3.5	80	250	2×10^{11}	2.5×10^{8}	IMPROPER CATHODE UTILIZATION
CX-1574 #2	25	8.5	3.5	80	250	2×10^{11}	1.2×10^{9}	CATHODE DEPLETION
CX-1574C	35	11	5	140	500	2×10^{11}	1.0×10^{8}	INSTALLED IN LASER
CX-1625	35	10	5	130	500	1×10^{11}	2.5×10^{9}	HEATER LEAD

LASER CIRCUITS

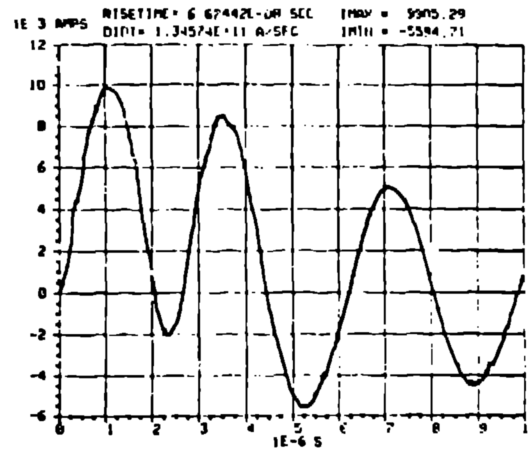
CX-1573C	35 kV	12	2	25	10	3×10^{11}		ACCUMULATING
CX-1574C	20 kV	6.5	1.2	55	250	2.5×10^{10}	2×10^{8}	ACCUMULATING
CX-1625	30 kV	10	4	up to 130	1–250	1.3×10^{11}	6.7×10^{7}	ACCUMULATING



CX-1625 TEST CIRCUIT CURRENT WAVEFORM

2kA/div Vert 100nS/div Horz

Figure 2a.



CX-1625 LASER CIRCUIT CURRENT WAVEFORM

2kA/div Vert 100nS/div Horz

Figure 2b.

tetrode and the pentode tubes. Whereas both the tubes gave optimum performance with two triggers, the time delay between the triggers was far less critical in the pentode tube than in the tetrodes. Also, a higher value of di/dt could be reached (without arcing) in the pentode than in the tetrode [5]. Jitter was the same in the CX-1574C as in the tetrode version. (It should be noted that the triggers used in all the testing had a jitter of ±180 pS peak to peak.) A comfortable power limit for the CX-1574 and C version at short pulse high rep rate conditions was found to be about 15 kW average in oil and 10 kW average in air. Grid emission was detected at RMS currents of 120 amps in oil and at grid flange temperatures of 250°C in air. Grid heating was found to be the limiting factor of both the CX-1574 and the CX-1574C. These levels correspond to a π b factor of 5×10^{17} and 3.5×10^{17}.

Lifetesting was not performed on the CX-1574C. After 120 h of evaluation at rated voltage and current the tube was installed in a 250 pps 250 mJ XeCl laser. Fitting the laser with tube increased the output power from 65 to 75 W. This increase in power was determined to be due to the lower switching loss of the pentode design. To date another 2×10^8 shots have been accumulated on the CX-1574C in the laser without a missed pulse. Thyratron life data in the laser circuit cannot be obtained as fast as in the test circuit because of the frequent maintenance (downtime) required to keep the laser operational. Laser electrode life is limited to about 2×10^8 shots or 222 h after which a major overhaul is necessary to refurbish the laser.

The next thyratron investigated was the CX-1625 metal/ceramic pentode. Three of these tubes were evaluated, one to end of life. The CX-1625 differs from the other types tested as it has a dispenser cathode rather than an oxide cathode. In an oxide cathode the emissive material is sprayed onto the cathode surface. The dispenser has the emitter impregnated into a porous tungsten matrix. Dispenser cathodes are far more resistant to thermal evaporation and damage due to arcing. As well as these points, dispenser cathodes can uniformly emit 100 to 200 amps/cm^2 compared to the 30 amps/cm^2 for oxide-coated cathodes. Refer to Table 1 for the electrical parameters relating to the test and laser circuits and Fig. 2 for the tube current waveforms. Optimum switching performance was again achieved with the dual triggering method. The RF radiation of the CX-1625 was 0.2 mW/cm^2 compared to 50 mW/cm^2 for the CX-1574C. Reduced RF radiation is a result of the metal envelope design on the CX-1625. Peak forward and reverse current carrying capability (without sparking) was much greater in the CX-1625 and jitter was a factor of 2 less than any of the tubes tested. Jitter of the CX-1625 at 100 h was measured at ±400 pS and at 1200 h ±800 pS. In the test circuit the first CX-1625 had reached 2.5×10^9 shots when the lug on the heater lead failed and heater power was lost. The CX-1625 life test was operated continuously* for 1250 h without a missed pulse or malfunction at the 20 kW average power level in an oil environment. Cooling was required to maintain the oil temperature at or below 130°F. Ambient temperatures above 130°F could not provide sufficient heat transfer from the anode to maintain voltage holdoff. Anode power losses in the reverse direction are 6 to 10 times higher than in the forward direction. At 50% current reversal and 500 pps, which this tube was operated, anode heating becomes the dominant loss factor in the thyratron. Excessive anode temperature, or lack of heat removal, would cause gas density gradients to form in the tube. As long as the thyratron was discharging, the reservoir voltage could be increased to reduce tube losses. When high voltage was removed, the anode would cool, the gas density in the grid/anode region would increase, and holdoff would be lost. Optimizing the reservoir power would allow operation at both high and low rep rates. This effect of gas density gradients is called gas pumping. All of the hollow anode thyratrons exhibit this behavior but it is more noticeable at the higher rep rates and large reverse currents. In overall performance, the CX-1625 was the best of all the tubes tested. This is characteristic of the metal/ceramic design but more so to the dispenser cathode.

Another CX-1625 has been operating in a 125 W average power XeCl experimental laser for the last seven months. Because this laser is a development device, shot accumulation is rather slow. However, the tube has behaved just as it did in the test circuit and has run flawlessly. The current waveform in Figure 2B was taken during laser operation.

The last thyratron to be tested was the CX-1573C pentode. This tube is a smaller version of the CX-1574C and behaves exactly in every respect as its larger counterpart except in the power-handling capability. An average power input of 5 kW was all the CX-1573C could handle reliably at short pulse duty with 50% reverse current. Grid emission first became noticeable at 55 amps RMS. Two CX-1573Cs were tested but no conclusive life data has been obtained thus far. The first CX-1573C operated for 35 h at 35 kV, 10 kA forward, 5 kA reverse, 200-ns pulsewidth and a rep rate of 250 pps. Even though the tube experienced no problems, when high voltage was removed, the first grid-cooled, warped and shorted internally. The autopsy revealed severe heat damage to the internal structure of the tube. Testing of the second CX-1573C indicated that this tube is good only at fairly low powers. The second CX-1573C was then installed in a 10 pps, 5 J per pulse laser. Peak current in this particular laser is approximately 20 kA. This laser is also an experimental device and substantial no life data has been accumulated yet.

Conclusion

Thyratrons having the ability to conduct in the reverse direction without sustaining damage are ideal for excimer lasers or any type pulsed circuit with a low impedance unstable load. These tubes are also suited to experimental circuits which are not optimized and where changes in the circuit can impress high amounts of reverse voltage on the switch. Hollow anode thyratrons eliminate the need for snubber diodes and end-of-line clippers which are needed to protect conventional thyratrons. Having the ability to conduct in the reverse direction does affect the recovery time slightly. The pentode design of the C series and the CX-1625 makes up for longer recovery time by shielding the cathode from the influence of the anode during recharge. The CX-1625 functioned properly at rep-rates to 1000 pps at full-rated voltage at the discharge parameters described in Table 1. All the tubes tested had recovery times comparable to conventional thyratrons. Consistency between tubes of the same type was excellent. No aging or conditioning was required of any of the 10 tubes tested. All of the tubes could be started at full voltage and rep rate in both the laser and test circuits right from the box. This is an important feature for industrial applications where maintainability is considered and excessive downtime cannot be tolerated. For this reason the CX-1574C has been chosen as the switching element for a multiple laser materials processing facility at Los Alamos National Laboratory.

Determining the limitations and capabilities of thyratrons in test circuits does not always relate to the way devices will perform in actual use. Likewise, the behavior of the thyratrons at rep rated, short-pulse, high di/dt conditions may be different in other type circuits. Often, a thyratron will behave very differently in a simulative test circuit to the way it will in the actual equipment, which adds unnecessary problems to the development process. In the course of testing and using the thyratrons described, this was not the case. Tube performance was the same in both the test and laser circuits. Consistency in performance between test and end use circuits allows for more accurate component life scaling in new designs. Data acquired in the last two years from hollow anode thyratron testing closed the loop in life scaling formulas for short-pulse, high rep rate circuits.

*Test was halted every 100 h for ~ min to measure cathode condition.

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